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## RESEARCH ARTICLE

# Trends in summer heatwaves in central Asia from 1917 to 2016: Association with large-scale atmospheric circulation patterns

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## Abstract

The changes in the frequency, duration, and intensity of summer heatwaves over central Asia during the period 1917–2016 were studied. On average, the frequency, duration, and intensity of heatwaves showed significant positive trends during the period 1917–2016, with enhanced rates during the last 50 years. During 1967–2016, the heatwave indices increased significantly in most of central Asia, especially in the western part. The number of heatwaves has increased by 1.3 times since the 1960s. Remarkable changes in the frequency and duration of heatwaves occurred during the 1990s in association with the inter-decadal shift in the Silk Road pattern of atmospheric circulation around 1997. The results based on the ERA-Interim reanalysis data set were well-matched with the station observations during the period 1979–2016, whereas those based on the NCEP-NCAR data set were less well matched. Heatwaves in central Asia were closely related to a zonal wave circulation pattern at 500 hPa with a centre of positive geopotential height anomalies over central Asia. This anomalous circulation pattern was rapidly enhanced during the 1990s, suggesting that large-scale patterns of atmospheric circulation had a role in modulating the occurrence of heatwaves in central Asia.

## KEYWORDS

atmospheric circulation, central Asia, climate trends, heatwaves

## 1 | INTRODUCTION

Heatwaves can have widespread effects on human health and mortality (Luber and McGeehin, 2008; McMichael and Lindgren, 2011), the regional economy (Easterling *et al.*, 2000; Zander *et al.*, 2015), and biophysical systems (Welbergen *et al.*, 2008; Karoly, 2009). Recent examples include the record-breaking heatwave in Europe in 2003 and the Russia heatwave in 2010, which caused unprecedented heat-related death rolls (Christoph and Gerd, 2004; Russo *et al.*, 2015), and the 2013 heatwave in eastern China, which

caused widespread droughts and the loss of crops (Hou *et al.*, 2014; Xia *et al.*, 2016). Many studies have been carried out on the effects of climate change on global and regional heatwaves (Meehl and Tebaldi, 2004; Ding *et al.*, 2010; Perkins-Kirkpatrick *et al.*, 2016; Zhou and Wang, 2016). However, there is still lack of studies on heatwaves in particular geographical regions. One of the difficulties in studying heatwaves is the lack of high-quality, long-term climate data with an appropriate temporal resolution (Easterling *et al.*, 2000), at least daily maximum temperature data are required for estimation of the characteristics of heatwaves.

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Central Asia is a typical arid and semi-arid region in the hinterland of the Eurasian Continent. Water scarcity, land degradation, and a lack of emergency management capacity have increased its vulnerability to a number of natural hazards, including heatwaves (Pollner *et al.*, 2010; Hu *et al.*, 2015; Howard and Howard, 2016). Over the past century, surface warming has been 20–40% higher over global drylands than over more humid lands (Huang *et al.*, 2017). Therefore, drylands such as central Asia are at higher risk from extreme temperatures. During the period 1990–2010, extreme temperature events in this region caused damage costing US\$ 1,000 million, the most serious meteorological disasters in terms of economic loss in central Asia (Yang *et al.*, 2016).

However, our knowledge of the effects of climate change on heatwaves in central Asia remains limited. Previous studies of climate change in central Asia were mainly based on variations in the mean temperature. Using multiple data sets, Hu *et al.* (2014) found a significant increasing trend ( $0.36\text{--}0.42^\circ\text{C}\cdot\text{decade}^{-1}$ ) in the mean surface air temperature in central Asia from 1979 to 2011. Heatwaves may become more frequent and intense with an increase in the mean temperature. However, the scarcity or lack of long-term, homogeneous daily observations may lead to large uncertainties in studies of these events in central Asia (Klein Tank *et al.*, 2006; Mamtimin *et al.*, 2011; Hu *et al.*, 2014). It has been well-known that non-climate factors such as changes in station location, environment, instrumentation, etc. can bias statistical characteristics of climatic series (Trewin and Trevitt, 1996; Li and Yan, 2010; Yan *et al.*, 2014). Homogenization of the long-term meteorological observation series in central Asia has not been well studied. It is beneficial to study regional climate changes based on multiple data sets (Hu *et al.*, 2014). Reanalysis data sets have been widely used in regional climate studies (Song and Zhang, 2007; Bao and Zhang, 2012), but their suitability and accuracy for describing the effects of climate change on heatwaves in central Asia need to be evaluated by comparison with station observations.

This study analysed several heatwave indices in central Asia for the periods 1917–2016 and 1967–2016 based on quality-controlled and homogenized station observations. The quality of two widely used reanalysis data sets, the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR; Kalnay *et al.*, 1996) and the ERA-Interim (Dee *et al.*, 2011) data sets, was then assessed with regard to their ability to describe the variations in heatwave climate during the overlapping period of 1979–2016. The link between the change in heatwaves and atmospheric circulation was studied in an attempt to understand the underlying mechanisms.

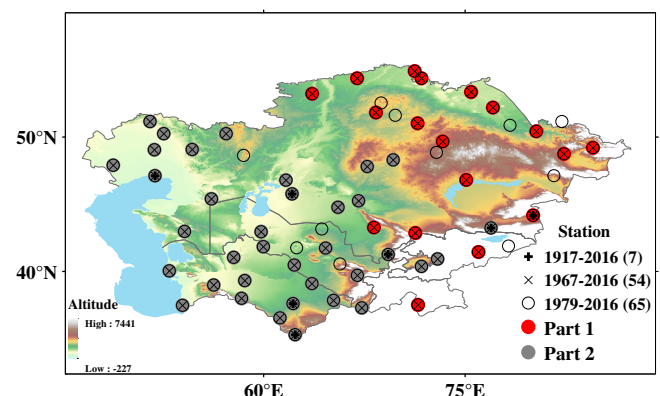
## 2 | DATA AND METHODS

### 2.1 | Study region

The term “central Asia” has been used to refer to the five inland countries to the south of Russia and west of China (Mayhew *et al.*, 2004), although it may also cover a wider region including western China and Mongolia (Le Houerou, 2005). In the present study, central Asia was used to refer to five countries—Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan—where there have been relatively few studies of the effects of climate change on heatwaves. Our study area covers about  $3.5 \times 10^6 \text{ km}^2$  of an arid to semi-arid inland region ( $35^\circ\text{--}55.4^\circ\text{N}$ ,  $46.5^\circ\text{--}88^\circ\text{E}$ ) with a total population of more than 57 million people (Population Reference Bureau (PRB), 2002; Lioubimtseva and Cole, 2006).

### 2.2 | Station observations

Meteorological observations of the daily maximum surface air temperature ( $T_{\max}$ ) were collected from 65 stations in central Asia. We selected 20 and 30 stations from the National Climatic Data Center (NCDC) of the US National Oceanic and Atmospheric Administration for the periods 1967–2016 and 1979–2016, respectively, and 34 and 35 stations from the Global Historical Climatology Network-Daily (GHCN-D) for the periods 1967–2016 and 1979–2016, respectively. Among these stations, seven had long-term observations for the period 1917–2016 (Figure 1 and Table 1). The data history of these stations is shown in Table 1. Quality control of the observations involved two steps: (a) a summer with data missing for more than five consecutive days or a ratio of missing data  $>8\%$  was set as a



**FIGURE 1** Geographical location of the meteorological stations in central Asia with data spanning the periods 1917–2016 (7 stations), 1967–2016 (54 stations), and 1979–2016 (65 stations). The topography of the region is represented by different colours. Part 1 (red stations) and part 2 (grey stations) show the two subregions resulting from clustering analysis of the 54 stations in 1967–2016. Details can be found in section 3.1.1

**TABLE 1** Daily maximum surface air temperature (2 m) used in this study

Data set description	Data sources	Period	Station number
National Climatic Data Center (NCDC) of the US National Oceanic and Atmospheric Administration	ftp://ftp.ncdc.noaa.gov/pub/data/	1917–2016	0
	gsod/	1967–2016	20
		1979–2016	30
Global Historical Climatology Network-Daily (GHCN-D)	www.ncdc.noaa.gov/oa/climate/ghcn-daily/	1917–2016	7
		1967–2016	34
		1979–2016	35

missing year; and (b) stations with >10% missing years in the study period were excluded. Then, the Multiple Analysis of Series for Homogenization (MASH) method was applied to the daily maximum temperature data sets. MASH is a well-established method for homogenizing regional climate data (Szentimrey, 1999). It has been well applied in many

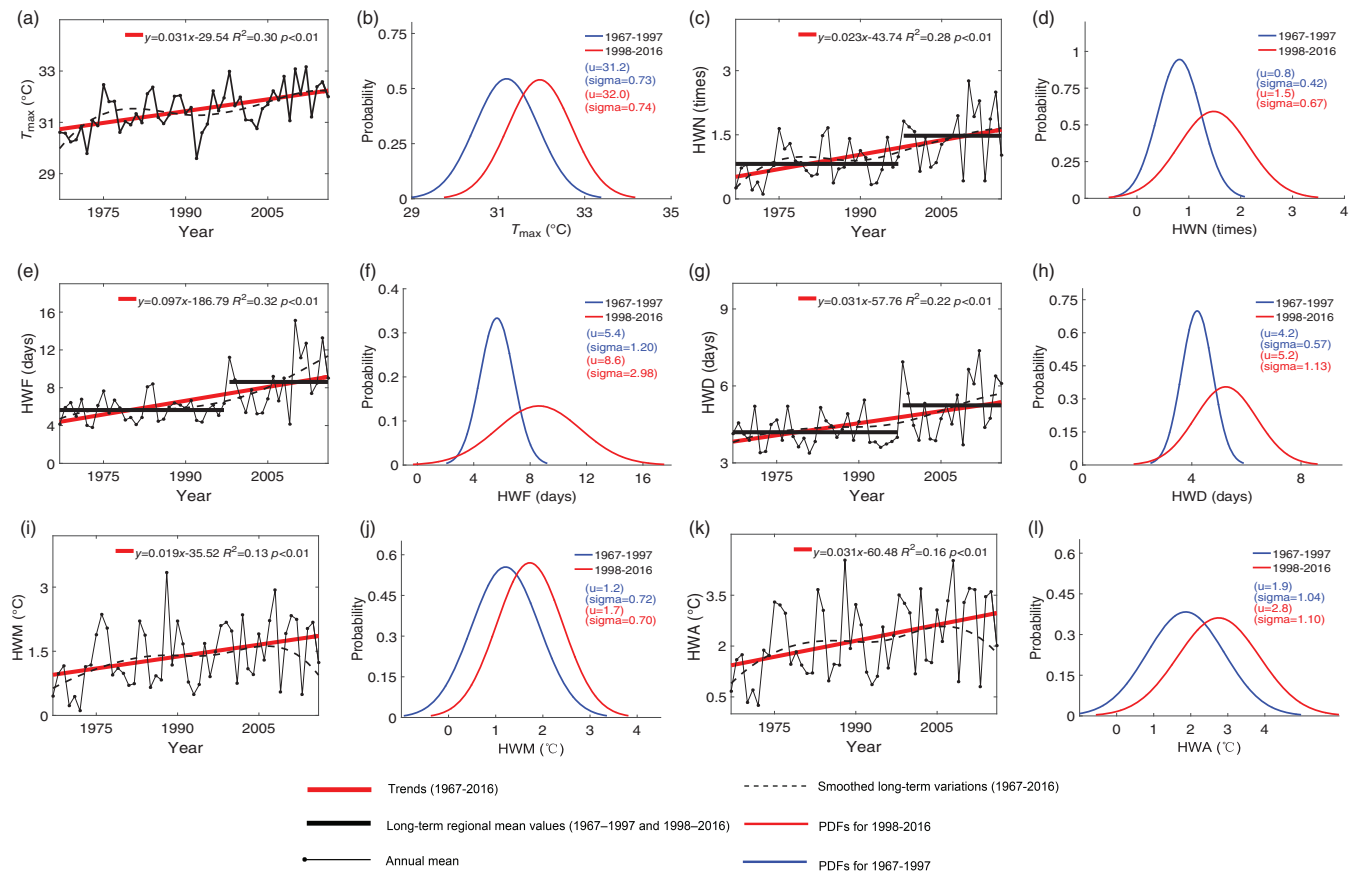
studies of regional climate changes (e.g., Manton *et al.*, 2001; Li and Yan, 2010; Li *et al.*, 2015).

### 2.3 | Reanalysis data sets

The NCEP/NCAR reanalysis data were obtained from [www.cdc.noaa.gov/](http://www.cdc.noaa.gov/) and covered the period from 1948 to the present day with a spatial resolution of  $2.5 \times 2.5^\circ$ . The ERA-Interim reanalysis data were obtained from the European Centre for Medium-Range Weather Forecasts website ([www.ecmwf.int/](http://www.ecmwf.int/)) and covered the period from 1979 to the present day with a spatial resolution of  $0.75 \times 0.75^\circ$  (Berrisford *et al.*, 2011). The period of overlap from 1979 to 2016 was used to compare the reanalysis data and the station observations in the study area. The  $T_{\max}$  time series of the grid closest to each meteorological station was used in the comparative analysis (Hu *et al.*, 2014).

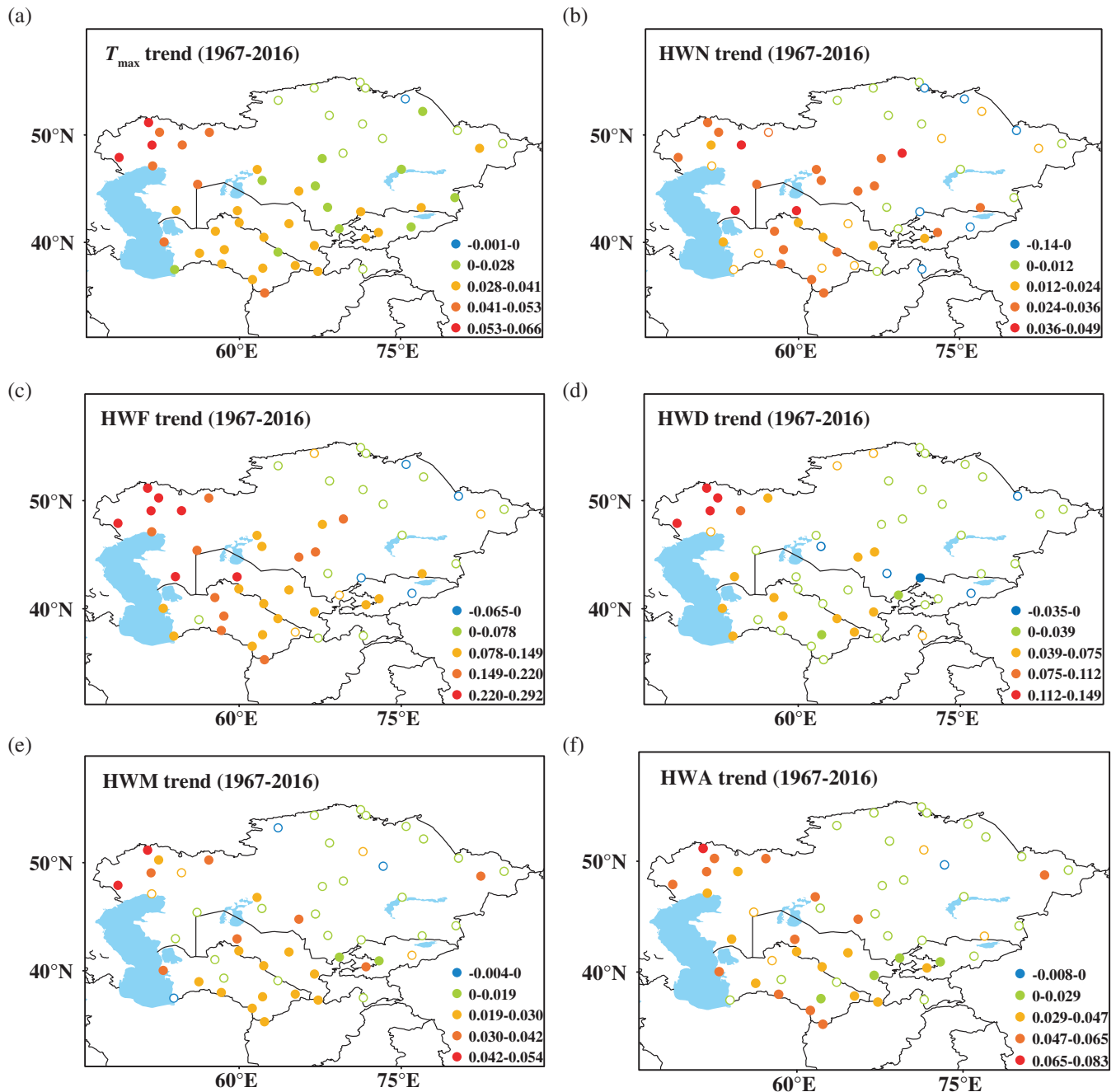
### 2.4 | Quantification of heatwaves

The daily threshold for extremely hot days was defined for each calendar day as the 90th percentile of  $T_{\max}$  based on all



**FIGURE 2** Regional mean series of (a)  $T_{\max}$ , (c) HWN, (e) HWF, (g) HWD, (i) HWM, and (k) HWA (black dashed lines indicate the smoothed long-term variations with the short-term variability filtered out via the ensemble empirical mode decomposition [EEMD] method) and the PDFs of (b)  $T_{\max}$ , (d) HWN, (f) HWF, (h) HWD, (j) HWM, and (l) HWA for central Asia for 1967–1997 and 1998–2016. For calculating the regional mean HWF and HWD, the stations for the years without a heatwave are excluded





**FIGURE 3** Geographical distribution of the linear trends of (a)  $T_{\max}$ , (b) HMN, (c) HWF, (d) HWD, (e) HWM, and (f) HWA during 1967–2016. The open circles indicate non-significant trends

the daily records during the reference period 1967–2016 (1979–2016 for the reanalysis data and the 65 stations) within an  $N$ -day window centred on the given calendar day (Yan *et al.*, 2002).  $N = 31$  was used to analyse the heatwaves, as suggested by Russo *et al.* (2014; 2015).

A hot day was defined as when  $T_{\max}$  was above the daily threshold. A heatwave event was defined as three or more consecutive hot days during the summer period (June–August). Two or more such consecutive hot periods with one normal day between were considered as one heatwave event.

Based on the framework of Fischer and Schär (2010) and Perkins *et al.* (2012), we defined five indices to represent the frequency, duration, and intensity of heatwaves: the heatwave number (HWN), the total number of heatwave events during a summer; the heatwave day frequency (HWF), the total number of days in heatwave events; the heatwave duration (HWD), the duration of the longest heatwave in a summer; the heatwave mean intensity (HWM), the mean heatwave intensity of all the heatwave events, the heatwave intensity being the highest 3-day

**TABLE 2** Climatological means and trends of regional means of  $T_{\max}$  and the heatwave indices in two subregions for the period 1967–2016

	Units	Trend (units/year)			Climatological mean		
		Part 1 (east)	Part 2 (west)	All	Part 1 (east)	Part 2 (west)	All
$T_{\max}$	°C	0.017**	0.037***	0.031***	27.12	33.67	31.48
HWN	times	0.006	0.031***	0.023***	1.06	1.08	1.07
HWF	days	0.024	0.129***	0.097***	6.67	6.80	6.77
HWD	days	0.012	0.039***	0.031***	4.44	4.64	4.60
HWM	°C	0.009	0.023***	0.019***	1.54	1.34	1.40
HWA	°C	0.015	0.040***	0.031***	2.43	2.09	2.20

\*The liner trend was significant at  $p < .1$  levels.

\*\*The liner trend was significant at  $p < .05$ .

\*\*\*The liner trend was significant at  $p < .01$ .

running mean  $T_{\max}$  anomaly ( $T_{\max}$  minus the threshold of the day) during an event; and the heatwave amplitude (HWA), the largest  $T_{\max}$  anomaly ( $T_{\max}$  minus the threshold of the day) during all the heatwave events.

### 3 | RESULTS

#### 3.1 | Spatial and temporal variations of $T_{\max}$ and heatwave indices

##### 3.1.1 | Variations in the period 1967–2016

Figure 2a shows the inter-annual variation of the regional mean  $T_{\max}$  during the summer months in central Asia. The long-term mean  $T_{\max}$  was about 31.5°C. There was a significant increasing trend of 0.31°C·decade<sup>-1</sup> during the period 1967–2016, comparable with the results of Hu *et al.* (2014). Figure 3a illustrates that the summer  $T_{\max}$  shows significant increasing trend at 80% of the stations. The stations in the southwest of the region recorded higher temperatures, although greater warming trends occurred in the western part of central Asia.

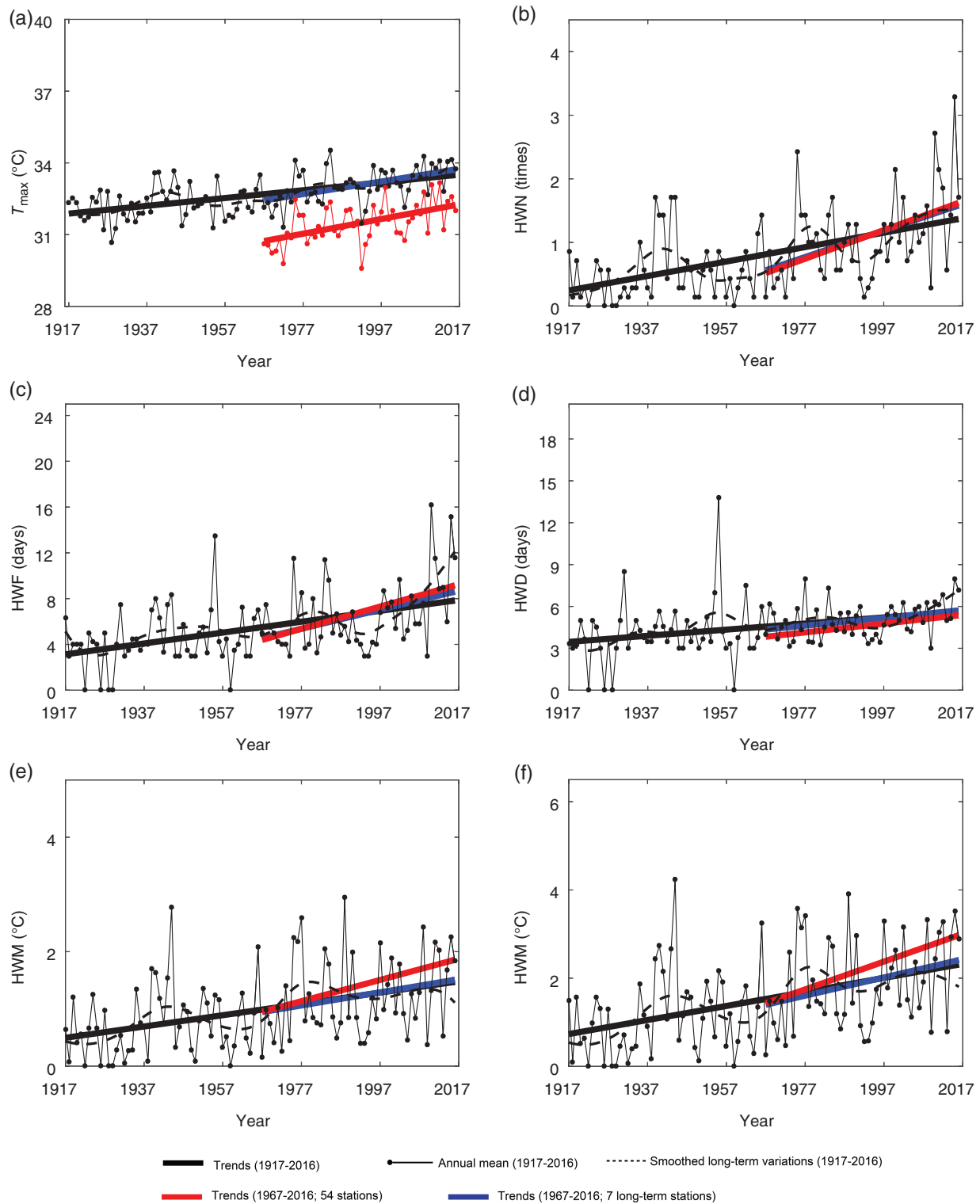
With increasing values of  $T_{\max}$ , heatwaves become more frequent. During the same period (1967–2016), the regional mean HWN showed a significant increasing trend of 0.23 events·decade<sup>-1</sup> ( $p < .01$ ), with a climatological mean of 1.07 events per summer (Figure 2c). In addition, there are strong regional differences in heatwave changes in central Asia. Based on *K*-means Clustering Algorithm (Wu *et al.*, 2008), observation stations could be divided into two subregions (Figure 1) according to six features, including longitude, latitude, liner trends of summer mean  $T_{\max}$ , HWN, HWF, and HWD during 1967–2016. Larger significantly increasing trends of HWN mainly occurred in western central Asia (Figure 3b), especially the region close to the Caspian Sea and the Aral Sea, which might be associated with the sea desiccation in this area (Rubinshtein *et al.*, 2014). The duration and intensity of heatwaves also

increased significantly. The increasing rates of regional mean were 0.97 days·decade<sup>-1</sup> (HWF), 0.31 days·decade<sup>-1</sup> (HWD), 0.19°C·decade<sup>-1</sup> (HWM), and 0.31°C·decade<sup>-1</sup> (HWA), respectively. The trends in the heatwave indices were generally larger and more significant in the west of central Asia than in the east (Figure 3b–f and Table 2).

However, although all the heatwave indices showed increasing trends from 1967 to 2016, there were different inter-decadal variations, especially around the 1990s. Figure 2c,e,g shows that the indices of HWN, HWF, and HWD during 1998–2016 were much larger than those during 1967–1997. Using the Mann–Kendall test, a rapid change was found around 1997. Taking HWF as an example, the average value changed from 5.4 days·year<sup>-1</sup> before 1997 to 8.6 days·year<sup>-1</sup> after 1997; the rate of trend changed from 0.01 days·year<sup>-1</sup> before 1997 to 0.19 days·year<sup>-1</sup> after 1997 (Figure 2e). For comparison, the indices for the heatwave intensity (HWM and HWA) did not show an obvious change around the same time based on the Mann–Kendall test; the trend during 1998–2016 was weaker ( $p > .1$ ) (Figure 2i,k). For the two subregions, there were remarkable changes of HWN, HWF, and HWD over the western central Asia in 1997, while the east did not find similar change at this time. Comparing the probability distribution functions (PDFs) of the heatwave indices between the two periods over central Asia, we see clear shifts of the PDFs towards larger values (Figure 2). The larger width of the PDF (a measure for the standard deviation of an index series) for the recent period suggests that the heatwave climate has greater inter-annual variability in the recent decades than in the earlier time. Changes of PDFs for the two subregions are similar with that of the entire region.

##### 3.1.2 | Variations in the period 1917–2016

There are seven stations with long-term observations which could be used to analyse the variations in the period 1917–2016 (Figure 1). Figure 4a shows that there has been a



**FIGURE 4** Regional mean series for the 7 long-term stations for the period 1917–2016 compared with the 54 stations for the period 1967–2016: (a)  $T_{\max}$ , (b) HWN, (c) HWF, (d) HWD, (e) HWM, and (f) HWA. The black dashed lines indicate the smoothed long-term variations with the short-term variability filtered out via the EEMD method

significantly increasing trend in the summer  $T_{\max}$  in central Asia during the last 100 years of  $0.16^{\circ}\text{C}\cdot\text{decade}^{-1}$ . In the last 50 years, this trend has increased to  $0.26^{\circ}\text{C}\cdot\text{decade}^{-1}$  (Table 3). Correspondingly, during 1917–2016, all the

heatwave indices showed a significantly increasing trend ( $p < .01$ ) of  $0.11$  times $\cdot\text{decade}^{-1}$  for HWN,  $0.39$  days $\cdot\text{decade}^{-1}$  for HWF,  $0.15$  days $\cdot\text{decade}^{-1}$  for HWD,  $0.10^{\circ}\text{C}\cdot\text{decade}^{-1}$  for HWM, and  $0.16^{\circ}\text{C}\cdot\text{decade}^{-1}$  for HWA

**TABLE 3** Climatological means and trends of regional means of  $T_{\max}$  and the heatwave indices for the periods 1917–2016 and 1967–2016 in seven stations with long-term observations

	Units	1967–2016 (seven stations)		1917–2016 (seven stations)	
		Trend (units/year)	Climatological mean	Trend (units/year)	Climatological mean
$T_{\max}$	°C	0.026***	33.08	0.016***	32.69
HWN	times	0.021***	1.07	0.011***	0.81
HWF	days	0.083***	6.57	0.039***	5.77
HWD	days	0.028**	5.03	0.015***	4.73
HWM	°C	0.012*	1.23	0.010***	0.98
HWA	°C	0.021**	1.90	0.016***	1.52

\*The liner trend was significant at  $p < .1$  levels.

\*\*The liner trend was significant at  $p < .05$ .

\*\*\*The liner trend was significant at  $p < .01$ .

(Table 3). The trends increased during the last 50 years. The Mann–Kendall test showed large increases in HWN and HWF around the late 1990s, consistent with the sharp increase in  $T_{\max}$  at the same time.

### 3.2 | Comparison of the results for the reanalysis data sets and the station data

Figure 5a shows the regional mean summer  $T_{\max}$  series based on the 65 station observations during 1979–2016 and those based on the two reanalysis data sets. The reanalysis data sets generally underestimated the temperature by about 0.7 and 1.8°C for the NCEP/NCAR and ERA-Interim data sets, respectively. This is partly because the extreme records are smoothed out in the reanalysis data sets (Freychet *et al.*, 2017) and partly because most of the stations are located on the plains which have lower average altitude, but the reanalysis data sets cover a greater range of topography in the region.

The correlation coefficients between the stations and the reanalysis data sets for the heatwave indices presented in Figure 5b–f were all significant ( $p < .01$ ). However, those between the stations and the NCEP/NCAR data set were smaller than those between the stations and the ERA-Interim data. Figure 5b–f shows that the trends in the heatwave indices based on the ERA-Interim data were close to the station observations, whereas those based on the NCEP/NCAR data were much smaller (Table 4).

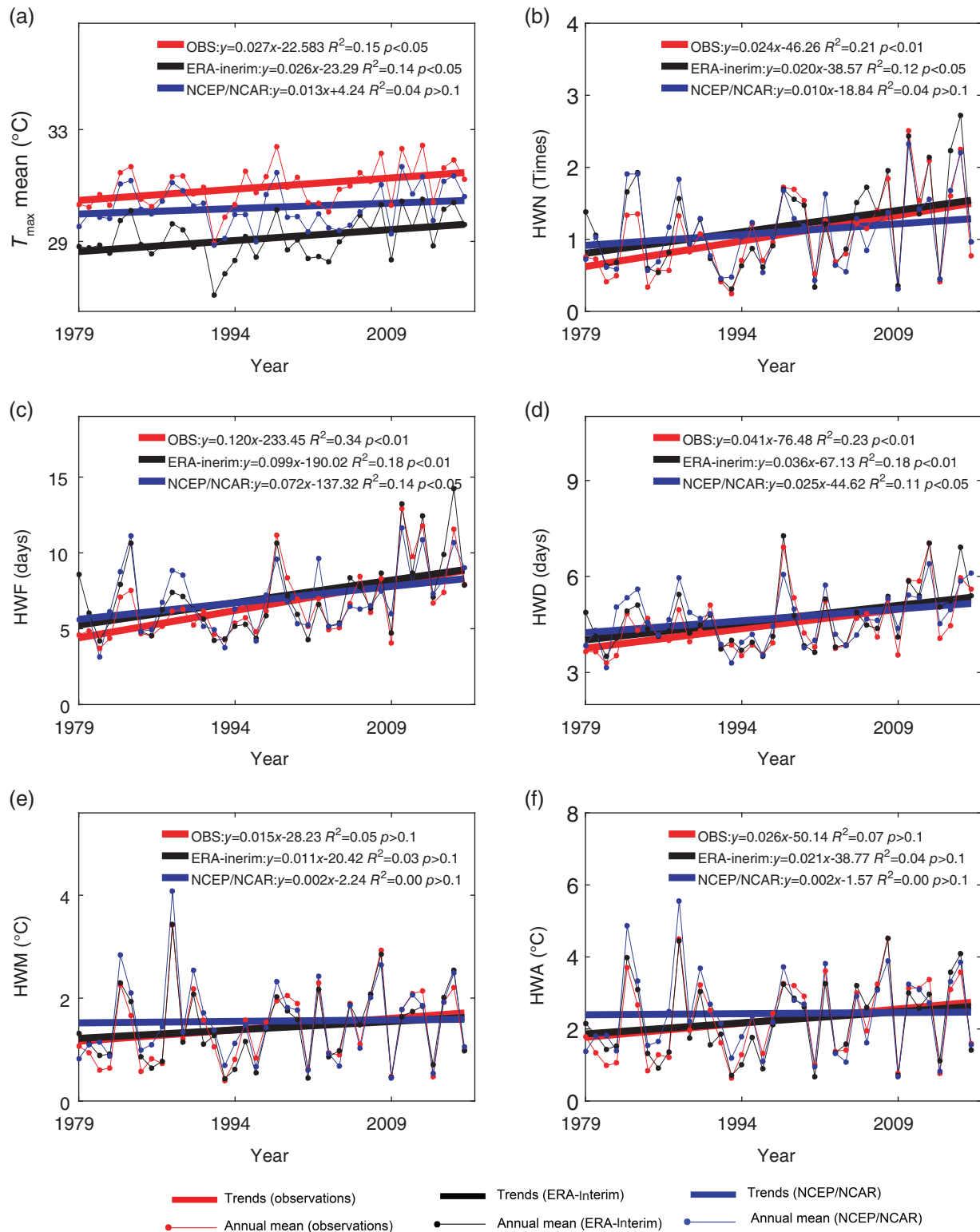
The geographical distribution of the trends of  $T_{\max}$  based on the ERA-Interim data was fairly consistent with that based on the station observations ( $p < .01$ ). By contrast, the spatial correlation between the station observations and the NCEP/NCAR data was not significant ( $p > .1$ ) (Figure 6a–c). For the geographical patterns of the trends in the heatwave indices during 1979–2016 (Figure 6d–r), the results based on the ERA-Interim data also matched the station observations well, whereas those based on NCEP/NCAR data did not. For

example, the geographical pattern of the trends of HWM based on the NCEP/NCAR data was very different from that based on the station observations ( $p > .1$ ), whereas the spatial correlation between the station observations and ERA-Interim data was significant ( $p < .001$ ; Figure 6m–o and Table 4).

These comparisons suggest that the ERA-Interim data set gave a good description of the temporal and geographical variations in the summer  $T_{\max}$  and heatwave indices in central Asia. The NCEP/NCAR reanalysis data set had a relatively poor performance in capturing the heatwave features in this region. This is partly due to the assimilation of more near-surface observations in the ERA-Interim data set (Simmons *et al.*, 2004; 2010; Dee *et al.*, 2011). The coarser resolution of the NCEP/NCAR data set may also explain some of these differences (Hu *et al.*, 2014).

### 3.3 | Relationship with atmospheric circulation

The composite analysis is performed for the following atmospheric variables in ERA-Interim data set: 500-hPa geopotential height, surface pressure, and horizontal wind at 850 hPa. Figure 7a,c,e shows the composite anomalies pattern of the 500-hPa geopotential height, surface pressure, and horizontal wind at 850 hPa for July for the 10 years of the highest frequencies of heatwaves in central Asia. Positive 500-hPa height anomalies (Figure 7a) and anticyclone circulation (Figure 7e) favour the anomalous descent of air in the lower troposphere, leading to more clear days and greater downwards solar radiation, and hence a greater potential for heatwaves during the summer period (Loikith and Broccoli, 2012). There appears to be a zonal wave train across mid-latitudes (Figure 7a), roughly consistent with the Silk Road pattern (Lu *et al.*, 2002), with an anomalous barotropic anticyclone near the Caspian Sea. The Silk Road pattern is a zonally oriented teleconnection pattern in the



**FIGURE 5** Comparisons of the regional mean time series during the period 1979–2016 between the station observations and the reanalysis results: (a)  $T_{\max}$ , (b) HMN, (c) HWF, (d) HWD, (e) HWM, and (f) HWA

Northern Hemisphere summer that takes the form of a stationary Rossby wave trapped in the jet stream (Enomoto *et al.*, 2003). It has been suggested that the inter-decadal variation of the Silk Road pattern has a crucial role in

modulating inter-decadal warming over Eurasia (Wang *et al.*, 2017). The Silk Road pattern showed an inter-decadal shift around 1997, which explains >40% of warming in eastern Europe and west and northeastern Asia (Wang *et al.*,



**TABLE 4** Climatological means and trends of regional mean  $T_{\max}$  and heatwave indices in central Asia during 1979–2016 based on station observations and the NCEP/NCAR and ERA-Interim reanalysis data sets

	Data sets	Climatological mean	Trend ( $\text{year}^{-1}$ )	CC1	CC2
$T_{\max}$ ( $^{\circ}\text{C}$ )	Observations	30.96	0.027**	1	1
	NCEP/NCAR	30.22	0.013	0.84***	−0.02
	ERA-Interim	29.12	0.026**	0.95***	0.75***
HWN	Observations	1.06	0.024***	1	1
	NCEP/NCAR	1.10	0.010	0.87***	0.19
	ERA-Interim	1.17	0.020**	0.92***	0.62***
HWF	Observations	6.62	0.120***	1	1
	NCEP/NCAR	6.96	0.072**	0.81***	0.16
	ERA-Interim	7.07	0.099***	0.92***	0.64***
HWD	Observations	4.51	0.041***	1	1
	NCEP/NCAR	4.70	0.025**	0.89***	0.42***
	ERA-Interim	4.68	0.036***	0.91***	0.69***
HWM ( $^{\circ}\text{C}$ )	Observations	1.44	0.015	1	1
	NCEP/NCAR	1.55	0.002	0.94***	0.08
	ERA-Interim	1.42	0.011	0.95***	0.50***
HWA ( $^{\circ}\text{C}$ )	Observations	2.25	0.026	1	1
	NCEP/NCAR	2.43	0.002	0.92***	0.12
	ERA-Interim	2.24	0.021	0.94***	0.38***

Note. CC1 is the temporal correlation coefficient of the regional mean indices. CC2 is the spatial correlation coefficient of the linear trends.

\*Correlation between the observations and reanalysis data sets was significant at  $p < .1$ .

\*\*Correlation between the observations and reanalysis data sets was significant at  $p < .05$ .

\*\*\*Correlation between the observations and reanalysis data sets was significant at  $p < .01$ .

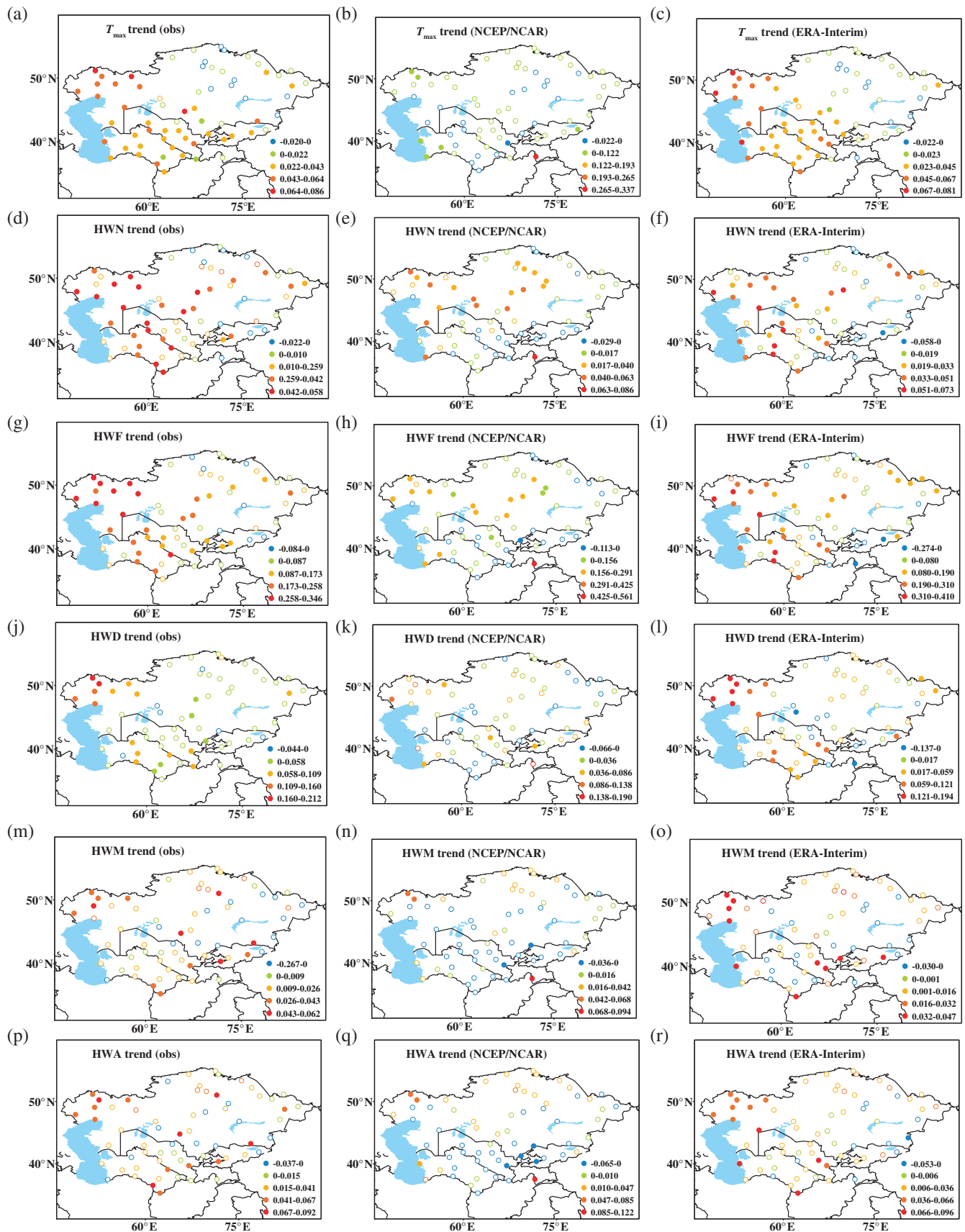
2017). The rapid increase in the frequency of heatwaves in central Asia also occurred around the late 1990s.

To investigate the inter-decadal change in the number of heatwaves during the 1990s, we compared the composite anomaly patterns of the 500-hPa geopotential height (Figure 7b), surface pressure (Figure 7d), and horizontal wind at 850 hPa (Figure 7f) between the periods 1988–1997 and 1998–2007. Figure 7b shows that there were positive anomalies in the 500-hPa height centred over central Asia during the period 1998–2007, but negative anomalies over central Asia during the earlier period. The wave train pattern during the period 1998–2007 was opposite to that in 1988–1997. The roughly opposite distribution of the 500-hPa geopotential height anomalies (Figure 7b) and the anomalous anticyclonic circulation (Figure 7f) in the later period suggests that there should have been a systematic change in the large-scale patterns of atmospheric circulation during the 1990s, which favoured the increase in the frequency of heatwaves in central Asia, consistent with the inter-decadal variation in the Silk Road pattern in the same period (Wang *et al.*, 2017). Therefore, the rapid change in the frequency of heatwaves in central Asia around 1997 was not an isolated phenomenon, but was associated with

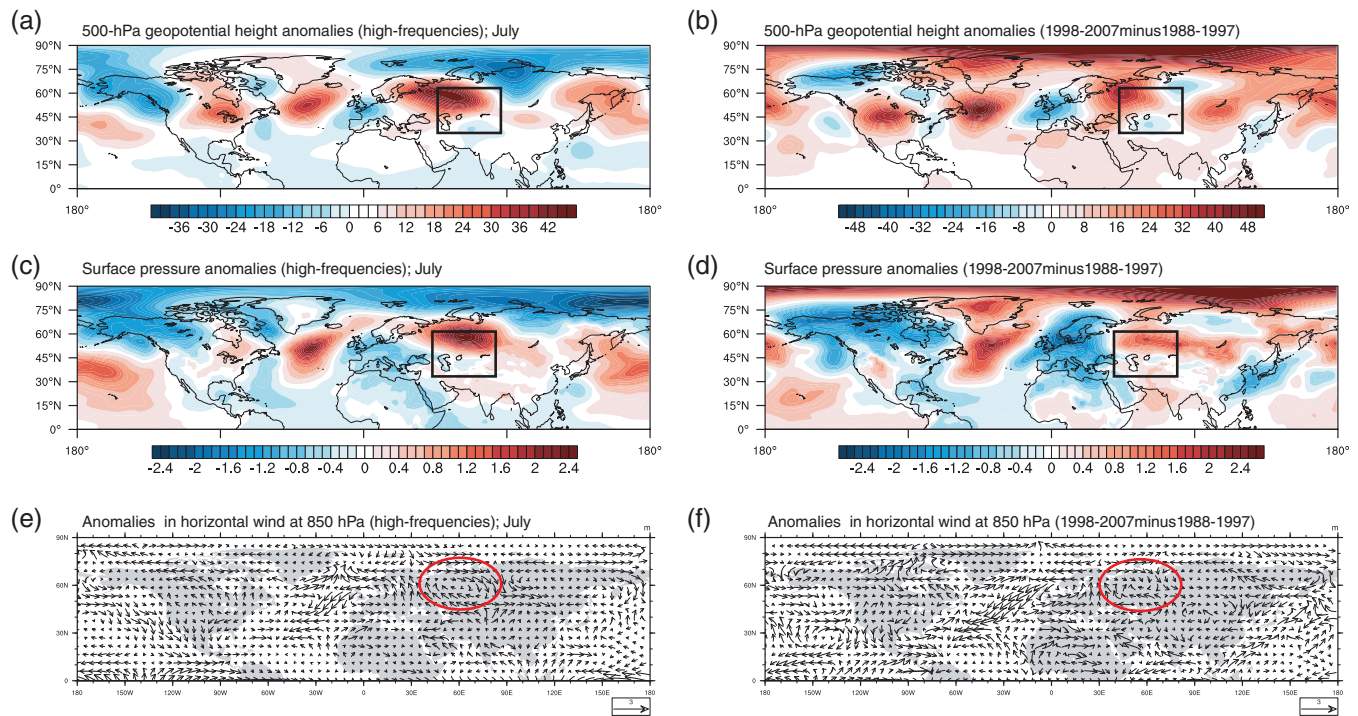
inter-decadal warming over a large area from eastern Europe and North Africa to the Tibetan Plateau and eastern Siberia (Wang *et al.*, 2017). These results highlight the importance of the changing Silk Road pattern to recent inter-decadal climate variations over Eurasia.

## 4 | DISCUSSION AND CONCLUSIONS

This work provides an overview of the changes in summer heatwaves in central Asia based on homogenized observations from the last 100 years. Significant increasing trends in the frequency, intensity, and duration of heatwaves were observed in most of central Asia, especially during the last 50 years in western central Asia. The geographical patterns of the trends in the heatwave indices were consistent with that of climatic warming trends ( $T_{\max}$ ) in the region, suggesting a direct role of large-scale climate warming in the increase in heatwaves. However, strong inter-decadal changes were evident in central Asia. In particular, there were rapid increases in the frequency and duration of heatwaves around the 1990s. The ERA-Interim reanalysis



**FIGURE 6** Geographical distribution of the linear trends in (a–c)  $T_{\max}$ , (d–f) HWN, (g–i) HWF, (j–l) HWD, (m–o) HWM, and (p–r) HWA during the 1979–2016, based on the (a, d, g, j, m, p) station observations, (b, e, h, k, n, q) NCEP/NCAR, and (c, f, i, l, o, r) ERA-Interim reanalysis data. The open circles indicate non-significant trends



**FIGURE 7** The composite anomalous patterns of (a) 500-hPa geopotential height, (c) surface pressure, and (e) horizontal wind at 850 hPa for the years of highest frequencies of heatwaves in central Asia (1983, 1988, 1989, 2000, 2002, 2005, 2008, 2010, 2011, and 2012); and the patterns of differences of (b) 500-hPa geopotential height, (d) surface pressure, and (f) horizontal wind at 850 hPa between the period 1998–2007 and 1988–1997. The anomalies were calculated against the mean climatology for 1979–2016

data set reproduces well the features of the heatwaves trends and the spatial variability in station observations, whereas the NCEP/NCAR data set shows marginal correlations with the observations in this region.

Our results indicate a centre of positive 500-hPa height anomalies and an anomalous anticyclonic circulation over the northwest of the region corresponding to the increasing occurrence of heatwave in central Asia. There were systematic changes in the large-scale atmospheric circulation around the 1990s favourable for the rapid increase in heatwaves in central Asia. This rapid change was associated with the inter-decadal shift in the Silk Road pattern, highlighting the importance of the changing Silk Road pattern to the recent inter-decadal climate warming and variations in climate extremes across the Eurasian continent. Detailed analyses of more atmospheric variables are beneficial for understanding the mechanisms underlying the effect of climate change on heatwaves in this region.

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